Greenhouse Gas Impacts of Ethanol from Iowa Corn: Life Cycle Analysis versus System-wide Accounting

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Abstract

Life cycle analysis (LCA) is the standard approach used to evaluate the greenhouse gas (GHG) benefits of biofuels. However, it is increasingly recognized that LCA results do not account for some impacts—including land use changes—that have important implications on GHGs. Thus, an alternative accounting system that goes beyond LCA is needed. In this paper, we contribute to the literature by laying out the basics of a system-wide accounting (SWA) method that takes into account all potential changes in GHGs resulting from biofuel expansion. We applied both LCA and SWA to assess the GHG impacts of ethanol based on Iowa corn.

Growing corn in rotation with soybeans generated 35% less GHG emissions than growing corn after corn. Based on average corn production, ethanol's GHG benefits were lower in 2007 than in 2006 because of an increase in continuous corn in 2007. When only additional corn was considered, ethanol emitted about 22% less GHGs than gasoline. Results from SWA varied with the choice of baseline and the definition of geographical boundaries. Using 2006 as a baseline and 2007 as a scenario, corn ethanol's benefits were about 20% of the emissions of gasoline. If we expand geographical limits beyond Iowa, but assume the same emission rates for soybean production and land use changes as those in Iowa, then corn ethanol generated more GHG emissions than gasoline. These results highlight the importance of boundary definition for both LCA and SWA.

Keywords: biofuels, corn ethanol, greenhouse gas, life cycle analysis, system-wide accounting.

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1. Introduction

As the United States begins to move toward putting an economic value on reducing greenhouse gas (GHG) emissions, the need for improved accounting standards becomes acute. Life cycle analysis (LCA), which involves the systematical collection and interpretation of material flow in all relevant processes of a product, has become the accepted procedure for determining GHG emissions of products ranging from transportation fuels to building materials to food production (Farrell et al., 2006; Hill et al., 2006). The LCA approach is also supported by government agencies such as the European Union (EC, 2007). The basic motivation of LCA is that to conduct a fair assessment of the environmental impacts of a product it is necessary to take into account all of the processes throughout the product's lifespan, including the extraction of raw material, the manufacturing processes that convert raw material into the product, and the utilization and disposal of the product. For many products, including fossil fuels, a standard LCA is generally all that is needed to understand GHG emission implications.

Accounting procedures for biological-based products, however, require additional considerations. Consider a country that expands production of an agricultural feedstock to produce biofuels. To understand how such an endeavor affects GHG emissions requires analysis of the GHG contents of all the inputs used to produce the feedstock as well as the inputs used to create the fuel from the feedstock. This is as far as most LCAs go. But expanded production of the feedstock does not just magically happen. Either current uses of the feedstock must be reduced to free up supply for production of biofuels or additional production must occur. If current uses are reduced, then the GHG emissions associated with the current use should be credited toward the biofuels because they are no longer being emitted. However, if an alternative product is used as a substitute for the current use of the feedstock, then the GHG implications of increased production of the substitute should also be counted as a debit. If current use is maintained, then the implications of expanded production of the feedstock need to be accounted for, including changes in crop acreage, production practices, and whether new land is brought into production. And lastly, if changes in land use in the biofuels-expanding region result in changed land-use decisions in other regions, then the GHG implications in these regions may have to be accounted for, depending on the definition of the system boundary in an analysis.

The need for accounting systems that take into account changes in production systems has been increasingly recognized (Delucchi, 2004; and Feehan and Peterson, 2004). In a recent report, the Clean Air Task Force noted that "current life-cycle analyses do not account for greenhouse gas emissions and other global warming impacts that may be caused by changes in land use; food, fuel, and materials markets" (CATF, 2007). Righelato and Spracklen (2007) showed that carbon changes related to land use changes could outweigh the avoided emissions through the substitution of petroleum fuel by biofuels. The contribution of this paper is two-fold: (*i*) to develop the beginnings of a protocol for system-wide accounting (SWA) systems that incorporates land use and other changes not included in LCA, and (*ii*) to apply the protocol to a case study of ethanol refined from Iowa corn. We will first lay out the basics of LCA for corn ethanol and gasoline. This serves as the beginning point for SWA because the components of LCA results can be used in SWA. We then assess the GHG impacts of ethanol from Iowa corn based on both types of accounting systems.

2. Life cycle accounting—ethanol versus gasoline

How much does corn-based ethanol change GHG emissions? Because ethanol is used to replace petroleum gasoline as a transportation fuel, a natural way to answer this question is by comparing the GHG emissions of ethanol and gasoline. Although the consumption of both fuels emits CO_2, emissions from gasoline are considered as net additions to atmospheric GHG stock because the emitted carbon comes from underground reservoirs. In contrast, because ethanol is produced from plant material that obtains carbon from the atmosphere, net CO_2 emissions from the burning of ethanol are zero. However, this by no means implies that corn-based ethanol is completely carbon neutral. The production of corn and the production of ethanol from corn consume energy and emit GHGs. Thus, the accounting of GHG impacts in the two production processes is central to the assessment of the net GHG benefits of ethanol.

Many studies have conducted LCA of the emissions from petroleum gasoline and corn-based ethanol. Different assumptions and data are often used in different studies. In Farrell et al. (2006), six representative analyses of fuel ethanol were evaluated to illustrate the range of assumptions and data found for the case of corn-based (*zea mays*, or maize) ethanol. The goal of most LCA for corn ethanol is to examine its net energy output and net GHG emissions, especially in comparison with petroleum gasoline. Defining system boundaries will be the most critical procedure in appropriately achieving the goal of an LCA. Although the system boundaries of corn ethanol can vary from study to study depending on the inclusion or exclusion of some specific processes, most LCA analyses would consider (*i*) the production of inputs used in growing corn, including seed, fertilizer (e.g., nitrogen, phosphorous, potassium), herbicide, pesticide, and energy; (*ii*) the application and utilization of inputs and the harvest of corn grain; (*iii*) the transportation of corn to biorefineries; and (*iv*) the conversion of corn to ethanol at biorefineries and the eventual burning of ethanol as transportation fuel. The life span of corn ethanol is often divided into two phases: the agronomy phase (the first two components) and the post-agronomy processing phase (the last two components). Dividing emissions into these two phases makes it easier to keep track of changes in GHG emissions attributable to ethanol.

The GHG impacts of ethanol are measured by GHG emissions intensity, e.g., tons or kilograms of CO_2 equivalent (CO_2e) per liter of ethanol. The lower the GHG intensity, the more beneficial is ethanol in terms of climate change mitigation. The key factors that determine GHG intensity are corn yields, the conversion rate of corn into ethanol, GHG emissions per bushel of corn at the agronomy phase, and GHG emissions per liter at the post-agricultural phase. Some agricultural practices used in corn production make a significant difference in corn yields and GHG emissions. Crop rotation is one example and will be emphasized in our study. Most LCA studies have not accounted for the impacts of GHG intensity caused by different agricultural practices. Two notable exceptions are Kim and Dale (2005, 2007), who conducted LCA for biofuels based on various cropping systems. However, they did not go beyond LCA.

We use $E_{LCA,eth\_rotation}$ to denote GHG emissions per liter of ethanol differentiating between different crop rotations. The energy contained in one liter of ethanol is about two-thirds of the energy contained in one liter of gasoline. However, to simplify exposition, we use “one liter of ethanol” to mean the amount of ethanol that is equivalent to one liter of gasoline in terms of energy content. Let $E_{ag,c\_rotation}$ and $E_{post,eth}$ be the emissions per liter of ethanol at the agronomy phase and the post-agronomy phase, respectively; then,

(1) $$E_{LCA,eth\_rotation} = E_{ag,c\_rotation} + E_{post,eth} .$$

Accounting at the agronomy phase is usually expressed in terms of emissions per unit (e.g., hectare) of land. Thus, $E_{ag,c\_rotation}$ is derived through the following formula that converts emissions per hectare to emissions per liter:

$$(2) \qquad E_{ag,c\_rotation} = \frac{\hat{E}_{ag,c\_rotation}(\frac{kg}{hectare})}{corn\ yield\ (\frac{ton}{hectare}) * conversion\ rate\ (\frac{liter}{ton})}.$$

We use “^” to make the distinction in units throughout the paper. Emissions at the agronomy phase depend on the quantity of inputs such as diesel fuel and fertilizer used as well as the efficiency with which they are converted to crop yields. Emissions at the post-agronomy phase are mainly affected by energy use at biorefineries. It is easy to see from equation (2) that the higher the corn yields, or the higher the conversion rate, the lower the GHG intensity will be. Both the corn yield potential and the conversion rate improve over time, as science and technology advance. In addition, actual corn yields are affected by specific agricultural management practices. For example, different rotations and different input uses can result in quite different yields.

The GHG benefits of corn ethanol, denoted by $\Delta E_{LCA,c\_rotation}$, can be derived by taking the difference between LCA emissions of one liter of ethanol and LCA emissions of one liter of gasoline, i.e.,

$$(3) \qquad \Delta E_{LCA,c\_rotation} = E_{LCA,gas} - E_{LCA,eth\_rotation},$$

where $E_{LCA,gas}$ represents all GHG emissions in the “well-to-wheel” life of gasoline, including carbon emitted from its eventual burning. In this paper, our focus is on the accounting of ethanol’s GHG benefits, and gasoline is only used as a basis for comparison. Thus, we will not examine LCA emissions of gasoline in detail; instead, results from the literature will be employed.

3. System-wide accounting—comparing an economy with and without ethanol

The purpose of assessing the net GHG benefits of corn-based ethanol is to understand whether more or less GHGs are emitted as a result of the replacement of some portion of gasoline used in an economy with ethanol. To fully answer this question for an economy, we need to compare the GHG emissions in the absence of ethanol with those in the presence of ethanol. In other words, we need SWA that considers all GHG emissions in the economy with ethanol and all GHG emissions in the same economy but without ethanol. By contrast, LCA compares the emissions in the life span of two products: ethanol and gasoline. Baseline emissions, defined here as emissions in the absence of ethanol, are irrelevant in LCA. That is, they are not accounted for, meaning that they are implicitly assumed to be zero or not affected by ethanol production. For example, the quantity of corn produced in the baseline has no effect on LCA of corn. In addition, it makes no difference whether corn for ethanol is produced on previously idled land or on previously cropped land. By explicitly comparing two states of the economy (with and without ethanol), SWA makes it explicit that there may be non-zero baseline emissions and what matters is the economy-wide net changes in GHG emissions.

In SWA, how the additional corn is produced and where it is produced are critical factors in determining net GHG emissions. When the additional corn is grown on idle land, ethanol's net GHG benefits will be affected by baseline emissions from such idle land. Similarly, when additional corn for ethanol comes from land previously devoted to other crops, there are emissions associated with the production and use of other crops in the baseline. In addition, more corn and less acreage devoted to other crops will change corn production practices and crop rotations. Finally, additional corn for ethanol could simply be diverted from other uses that involve baseline emissions that should be subtracted from ethanol's contribution to GHG emissions. Without ethanol, corn is mainly fed to livestock. Diversion of corn to ethanol from livestock would likely decrease livestock production and change the way that livestock are fed, both of which involve changes in GHG emissions.

An SWA protocol for corn ethanol needs to account explicitly for all of these possibilities. To illustrate how one can develop such a protocol, suppose that an economy has a total of 100L hectares of land available to grow corn and another crop (soybeans). Representing total hectares as 100L, with L being any positive constant, makes it easier to see the percentage shares of different land uses. Some land can be left idle. To simplify the presentation, we assume that corn grain is used to make ethanol that replaces gasoline. As a benchmark, we start with the baseline case without ethanol production, where land and output allocations are illustrated in Figure 1. In the figure, 10L hectares are devoted to continuous corn production, 60L hectares are devoted to corn production in rotation with soybean, and 30L hectares are left idle. We assume that for land with rotational corn production, half of the acreage is in corn and half is in soybeans in any given year.

Crop rotation has a major influence on how corn is produced. In the U.S. Corn Belt, corn is typically grown in rotation with soybeans. The soybean crop reduces nitrogen fertilizer applications and reduces pest pressure so fewer pesticides are needed. The yield of corn grown after soybeans is typically higher than corn grown after corn. Also, corn grown after soybeans requires less tillage than corn grown after corn. Let y_{cs} and y_{cc} be the corn yields for corn grown after soybeans and continuous corn, respectively; then total corn production in the baseline is

$(30y_{cs}+10\ y_{cc})L$. The production of soybeans is $30Ly_s$, where y_s is soybean yield. Suppose total gasoline use is 100G liters. Similar to L, G can be any positive constant. Then emissions in the baseline are as follows:

$$
\begin{aligned}
TE_{base,ag} &= L*\left[30*\hat{E}_{ag,s\_cs}+30*\hat{E}_{ag,c\_cs}+10*\hat{E}_{ag,c\_cc}+30*\hat{E}_{ag,idle}\right] \\
TE_{base,post} &= L*\left[(30y_{cs}+10y_{cc})*E_{post,food\_c}+30y_s*E_{post,s}+0*E_{post,eth}\right] \\
TE_{base,gas} &= G*100*E_{LCA,gas} \\
TE_{base,all} &= TE_{base,ag}+TE_{base,post}+TE_{base,gas}.
\end{aligned} \tag{4}
$$

The definitions of all emissions coefficients are described in Table 1. Note that emissions at the agronomy phase are differentiated by the two rotations: continuous corn ($\hat{E}_{ag,c\_cc}$) and corn in rotation with soybeans ($\hat{E}_{ag,c\_cs}$). There are a few factors in (4) that are important for SWA but not included in LCA of corn ethanol: emissions from growing soybeans ($\hat{E}_{ag,s\_cs}$), emissions associated with the use of soybeans ($E_{post,s}$), emissions from idle land ($\hat{E}_{ag,idle}$), and emissions associated with food use of corn ($E_{post,food\_c}$).

Each of the three sources of corn used in ethanol (displaced corn from food use, displacement of soybeans, and corn planted on previously idled land) impacts net GHG emissions. If ethanol is based on corn that would have been produced in the baseline, then the GHG difference from ethanol occurs after corn leaves the farmgate. For corn diverted from the food chain, $\Delta E_{SWA,food}$ denotes the net GHG impacts per liter of ethanol based on SWA. It is easy to see that

$$
\begin{aligned}
\Delta E_{SWA,food} &= E_{LCA,gas}-E_{post,eth}+\frac{1}{d}E_{post,food\_c} \\
&= \Delta E_{LCA,c\_cc}+\frac{1}{d}E_{post,food\_c}+\frac{1}{y_{cc}d}\hat{E}_{ag,c\_cc},
\end{aligned} \tag{5}
$$

where *d* converts metric tons of corn into liters of ethanol. When ethanol displaces gasoline, we avoid the GHG emissions, $E_{LCA,gas}$. However, this is not ethanol's net GHG benefits because of post-agronomy emissions generated when corn is devoted to food use and the emissions associated with corn production, which should be given as credits to ethanol's GHG benefits. Because of the credit, the GHG benefits from ethanol based on existing corn are higher under SWA than under LCA.

When corn for ethanol is grown on land that was idle in the baseline, SWA differs from LCA in two ways. The first is emissions from idle land in the baseline, which are likely negative, as idle land, which was under production in the recent past, typically sequesters carbon. The second is emissions from the conversion of idle land to corn production, which is usually positive because soil carbon will likely be released when cultivation happens. Suppose continuous corn production is used on the newly converted area. Then the net GHG impacts per liter of ethanol from corn grown on idle land can be calculated as follows:

$$\begin{aligned} \Delta E_{SWA,idle} &= E_{LCA,gas} - E_{post,eth} + \frac{1}{y_{cc}d}[\hat{E}_{ag,idle} - \hat{E}_{ag,c\_cc} - \hat{E}_{conv,idle\_cc}] \\ &= \Delta E_{LCA,c\_cc} + \frac{1}{y_{cc}d}[\hat{E}_{ag,idle} - \hat{E}_{conv,idle\_cc}]. \end{aligned} \tag{6}$$

Accounting for GHG changes becomes more complicated when there is a production shift from soybeans to corn. Suppose such a production shift occurs on one hectare of land. For illustration purpose, assume that in the baseline the hectare is split equally between corn and soybeans in any given year. Also assume that only the increase in corn production is used for ethanol, i.e., food use of corn remains unchanged. Then the net GHG impacts of one liter of corn ethanol based on the rotation shift can be counted as follows:

$$
\begin{aligned}
\Delta E_{SWA,cs\_cc} &= E_{LCA,gas} - E_{post,eth} + \frac{1}{(y_{cc} - 0.5y_{cs})d}[0.5\hat{E}_{ag,s\_cs} + 0.5\hat{E}_{ag,c\_cs} \\
&\qquad - \hat{E}_{ag,c\_cc} - \hat{E}_{conv,cs\_cc} + 0.5y_s * E_{post,s}] \\
&= \Delta E_{LCA,c\_cc} + \frac{1}{(y_{cc} - 0.5y_{cs})d}[0.5\hat{E}_{ag,s\_cs} + 0.5\hat{E}_{ag,c\_cs} \\
&\qquad - 0.5\frac{\mathrm{y_{cs}}}{\mathrm{y_{cc}}}\hat{E}_{ag,c\_cc} - \hat{E}_{conv,cs\_cc} + 0.5y_s * E_{post,s}].
\end{aligned} \tag{7}
$$

The term $(y_{cc} - 0.5y_{cs})$ is the additional corn obtained through a shift from a corn-soybean to a corn-corn rotation on one hectare of land. In general, y_{cs} is higher than y_{cc} because of rotational effects.

Several differences between SWA and LCA are clear from (7). First, since soybean production is replaced by corn production, the avoided emissions from soybeans ($\hat{E}_{ag,s\_cs}$) are counted as part of ethanol's benefits. The coefficient 0.5 reflects that half of the hectare was originally in corn and half was in soybeans. Second, emissions from corn grown after soybeans are part of the baseline emissions ($\hat{E}_{ag,c\_cs}$); thus, they appear as a credit to ethanol because they no longer occur after the rotation shift. Third, SWA accounts for the additional emissions that occur at the agronomy stage from growing continuous corn rather than corn after soybeans ($\hat{E}_{ag,c\_cc}$). Fourth, SWA incorporates potential changes in soil carbon, denoted as $\hat{E}_{conv,cs\_cc}$, that occur as rotation changes. And fifth, since soybeans are no longer grown on the hectare, the avoided emissions associated with the use of soybeans, $E_{post,s}$, are also considered as a benefit of corn ethanol in SWA.

Although the GHG impacts of corn going to ethanol have been presented in equations (5), (6), and (7) separately by source, in reality corn for ethanol will come from all three sources. The share from each source will vary depending on total ethanol production and market forces. Thus, the net GHG benefits of corn ethanol can be calculated as a weighted average across the three different sources. For example, suppose the amount of ethanol generated is 30y_{cc}dL liters, which is based on the following land use changes: 10L hectares are converted from idle land to continuous corn production and 40L hectares are converted from a corn-soybean rotation to continuous corn production. Conversion from idle land and a rotation shift generates 10y_{cc}L and 40(y_{cc}-0.5y_{cs})L tons of corn, respectively. The term (y_{cc}-0.5y_{cs}) represents the additional corn per hectare obtained from a rotation shift. Food use will be reduced by 20(y_{cs}-y_{cc})L so that the total corn for ethanol is 30y_{cc}L tons. The distribution of land and output is illustrated in Figure 2. For the 30y_{cc}dL liters of ethanol generated this way, we can calculate the net GHG benefits as follows:

$$\begin{aligned}\Delta TE_{SWA} &= Ld[40(y_{cc}-0.5y_{cs})*\Delta E_{SWA,cs\_cc}+10y_{cc}*\Delta E_{SWA,idle}+20(y_{cs}-y_{cc})*\Delta E_{SWA,food}] \\ &= \Delta TE_{LCA,c\_cc} + 40L*(0.5\hat{E}_{ag,s\_cs}+0.5\hat{E}_{ag,c\_cs}-0.5\frac{y_{cs}}{y_{cc}}\hat{E}_{ag,c\_cc} \\ &\quad -\hat{E}_{conv,cs\_cc}+0.5y_s*E_{post,s})+10L*(\hat{E}_{ag,idle}-\hat{E}_{conv,idle\_cc}) \\ &\quad +20(y_{cs}-y_{cc})L*(\frac{1}{d}E_{post,food\_c}+\frac{1}{y_{cc}d}\hat{E}_{ag,c\_cc}),\end{aligned} \tag{8}$$

where $\Delta TE_{LCA,c\_cc} = 30y_{cc}dL*(E_{LCA,gas}-E_{LCA,c\_cc}) = 30y_{cc}dL*(E_{LCA,gas}-E_{ag,c\_cc}-E_{post,eth})$. The total benefits based on LCA, $\Delta TE_{LCA,c\_cc}$, are just the difference between the LCA emissions of gasoline and ethanol, assuming that corn was grown after corn. Of course, LCA can be based on any rotation or an average of rotations. Equations (5)-(8) suggest that the LCA approach provides only a partial accounting of the GHG impacts of ethanol. However, this does not diminish the importance of LCA. In order to perform SWA, it is often necessary to have emissions data for the agronomy and post-agronomy phases that are obtained in LCA of corn ethanol. It is not clear whether LCA will overestimate or underestimate the GHG impacts of corn ethanol because emissions related to land use changes depend on soil properties, climate conditions, and other agricultural practices. We will illustrate next the impact of moving from LCA to SWA by analyzing the GHG implications of expanded ethanol production from corn in Iowa.

4. Greenhouse gas benefits of ethanol from Iowa corn

In this section, we examine the differences between LCA and SWA with an empirical example of ethanol refined from Iowa corn. Iowa is in the center of U.S. corn and ethanol production in the nation: it supplies 30% of the corn utilized by the U.S. ethanol industry and accommodates roughly the same percentage of overall ethanol plant capacity within its area (ICGA, 2007). We use the EBAMM (1.1) model for our estimation. The model was constructed by Farrel et al. (2006) and can be downloaded from their website (http://rael.berkeley.edu/EBAMM/). Results from both the agronomy and the post-agronomy phases can be obtained from EBAMM. One clear advantage of this model is that data sources and parameters are transparent and so it is easy to see the impacts of different assumptions. GHG emissions differ for different ethanol processing plants. Given that our focus is on the agronomy phase, industry-weighted averages are used regarding energy uses and conversion rates in the post-agronomy phase. Since the efficiency of ethanol plants advances over time, EBAMM was run with most recent parameter values. For the agronomy phase, we obtained data specifically for corn grown in Iowa.

4.1. Emissions in the post-agronomy phase

GHG emissions in the post-agronomy phase depend mainly on three factors: milling processes, energy sources, and coproduct distribution. Before 2000, wet mill plants dominated U.S. ethanol production because they were more profitable than dry mill plants. But the sharp increase in ethanol prices has made dry mill plants more popular because of their greater efficiency at turning corn into ethanol. Based on forecasts of the Food and Agricultural Policy Research Institute (FAPRI, 2007) for 2010, the conversion rates at dry and wet milling plants will be 415.75 and 405.32 liters per metric ton of corn, respectively. The 2010 share of ethanol production will be 87% for dry mills and 13% for wet mills. Energy requirements per liter of ethanol produced in 2010 for dry and wet mill plants will be 10.03 MJ/geL (i.e., megajoule per gasoline-equivalent liter) and 12.80 MJ/geL respectively (GREET model, version 1.8, 2007). We adopt these numbers given that they take into account ethanol plants that will be in operation in the near future. A major energy requirement in dry mill plants is the drying of distillers grains. Distributing the grains wet to local feedlots reduces energy use of a dry milling plant by 35% (Wang, Wu, and Huo, 2007). Iowa's ethanol plants market 75% of the distillers grains in dry form while the rest are sold wet (Hardy et al., 2006).

For the post-agronomy phase, we computed an industry average of 1.26 kg CO_2e/gL for GHG emissions. Baker and Babcock (2008) show that distillers grains will substitute for corn and soybean meal in cattle and hog rations. To calculate the amount of corn and soybeans displaced requires solving the least-cost feed rations problem with and without distillers grains being allowed to enter the least-cost solution and then comparing the amount of corn and soybeans in the two solutions. Baker and Babcock (2008) show that the greatest displacement will be in the rations of fed cattle. Each gasoline-equivalent liter of ethanol produces 5.24 kg of distillers grains. Baker and Babcock (2008) estimate that each kg of distillers grains displaces 0.579 kg of corn and 0.473 kg of soybean meal at a corn price of $4.26/bu and at a soybean meal price of $249 per ton. An emission rate of 0.356 kg CO_2e per kg of corn and 0.3321 kg CO_2e per kg of soybean meal implies a credit of 0.539 kg CO_2e/geL, which makes the net contribution at the biorefinery stage equal to 0.72 kg/geL.

4.2 Corn production in Iowa

Over 90% of field crop acreage in Iowa is devoted to corn and soybeans. In 2006 the ratio of corn acreage to soybean acreage was 1.24 (see Table 2). Because of increased demand for corn from the ethanol industry, the ratio increased to 1.63 in 2007. The two crops are grown primarily in two rotations: corn following soybeans (CS) and corn following corn (CC). Because soybeans are not planted after a crop of soybeans, we can deduce from Table 2 that 4.11 million hectares of corn were planted following soybeans in 2007. Subtracting this from 2007 corn acreage, we find that 1.68 million hectares of corn were planted on 2006 corn acreage. We assume that the difference in total areas (0.14 million hectares) between 2006 and 2007 was converted to corn from idle land and was planted using continuous corn production methods. If we consider the current distribution of rotation to be stationary, we have approximately 71% of Iowa corn produced in a corn-soybean rotation with 29% planted after corn.

The benefits of planting corn after soybeans rather than after corn are higher yields, lower levels of nitrogen (N) fertilizer and chemicals, lower tillage, and more timely planting and harvesting. Thus, GHG intensity is lower for corn planted after soybeans than for corn planted after corn because crop yield and N fertilizer rates are two key determinants of GHG emissions from the production of corn. A typical yield penalty associated with CC relative to CS is approximately 10%-15% in Iowa (Erickson and Lowenberg-DeBoer, 2005; Hennessy, 2006; DeWitt et al., 2002; Duffy and Correll, 2006). For our analysis, we use a 10% yield drag, as new corn hybrids and improved management have tended to shrink the disadvantage. Among inputs at the agricultural phase, N fertilizer has the highest energy content, which implies high GHG emissions (Graboski, 2002; Pimentel and Patzek, 2005). In addition, part of N fertilizer applied to soil is emitted as nitrous oxide through denitrification and nitrification processes. The global warming potential of nitrous oxide is about three hundred times more potent than that of CO_2. Therefore, the difference in N fertilizer application between the two rotations can make a large difference in the GHG emissions from corn production.

Besides rotation, yields are affected by soil and land properties as well as by climate conditions. To account for these differences, Iowa counties were classified as being either low yielding, medium yielding, or high yielding according to their trend yield level in 2007. In general, many farmers vary N rates according to yield potential. But some current guidelines for N application do not vary recommendations according to yield potential (Duffy and Smith, 2007; Sawyer et al., 2006). There is little concrete empirical data to support either uniform or varied application across land with different yield potential. Thus, we consider both scenarios in our analysis. The uniform rates are assumed to be 146 and 202 kg/ha for CS and CC, respectively. These rates are assumed to hold for the middle-yielding class under the varied rate scenario. In this scenario, application rates are increased by 17 kg/ha for the high-yielding counties and decreased by 17 kg/ha for low-yielding counties. Table 3 lists yields and major input application rates for the two rotations by the three land classes.

While CS requires lower levels of nitrogen than CC, the rates of phosphorous (P) and potassium (K) are in general higher for CS to compensate for the higher removal rate of phosphate (P_2O_5) and potash (K_2O). However, the GHG impacts of P and K fertilizer are minor relative to the effects of N fertilizer. We use P and K rates suggested by Iowa State University Extension (Duffy and Smith, 2007). Another input in corn production that has important GHG implications is limestone, which is applied to fields to adjust for soil pH. Limestone is usually applied every few years. Applied limestone is converted to lime (CaO) in the soil. Approximately 44% of its mass is released to the air as CO_2 (Wang, Wu, and Huo, 2007). Farrell et al. (2006) indicated that limestone application rate data are very dispersed among corn-producing states and among various GHG emission reports. Unlike most peer studies, here we apply a state-specific rate and avoid some of the associated variation. Based on the most recent data, Iowa's limestone application rate per year is 647 kg/ha for 2001 (NASS/USDA, 2007). Finally, we use a higher seed rate that matches Iowa's yields and omits energy related to irrigation, which is rarely used in Iowa. For other input data and parameters, which are mostly time invariant, we adopt the values in the "ethanol today" scenario of the EBAMM model.

4.3 Results based on life cycle analysis

Table 4 reports the GHG emissions factors in the agronomy phase. Producing corn after a crop of corn emits 35% more GHGs on average than corn produced after a crop of soybeans. This result has important implications because most additional corn planted for ethanol in Iowa is currently obtained through a rotation shift from CS to CC (see Table 2). If land of different classes is applied with the same N rate, then there are marked differences in GHG emissions (as high as 47.24 kg/ton of corn) among the classes. However, if we assume that higher land classes require higher N applications to reach their higher yield potential, then the differences among the classes are much smaller (at most 7.48 kg/ton of corn). In other words, the impact of higher (lower) yields is offset by the higher (lower) emissions associated with more (less) N application.

To obtain the LCA emissions of corn ethanol, we combine emissions in the agronomy and the post-agronomy phases. As shown by the first two columns of Figure 3, the results for the two rotations are 1.66 kg/geL and 2.0 kg/geL for corn in CS and CC rotations, respectively. The percentage difference between the rotations is smaller for the life cycle than for the agronomy phase because both rotations have the same emissions in the post-agronomy phase. A commonly used estimate of gasoline's LCA emissions is 2.96 kg/geL (Farrell et al., 2006). Compared to gasoline, this means that ethanol made from corn grown after soybeans reduces GHG emissions by 44%, while ethanol made from corn grown after corn achieves a 32% reduction. Both numbers are much larger than the results of some recent studies. These results are on the higher end of estimates in the literature (Farrell et al., 2006) because the more recent data used in our study consisted of more efficient corn production on the farm, and cleaner energy sources and higher conversion rates at ethanol plants.

To obtain an estimate of the overall GHG impacts of ethanol from Iowa corn, we can calculate the weighted average of LCA emissions of ethanol based on the amount of corn grown after soybeans and the amount grown after corn in Iowa. The weight is the share of the rotations, which may change from year to year. If we assume the acreage of CS rotation is the same as the soybean acreage, then we can obtain the share of each rotation in 2006 and 2007. Based on these shares, we computed that the average GHG emissions of ethanol made from Iowa corn were 1.72 kg/geL in 2006 and 1.78 kg/geL in 2007. These represent 42% and 40% reductions in GHG emissions, respectively.

It is perhaps more reasonable to consider that emissions in the agronomy phase of ethanol should be emissions associated with the production of "new" corn as a result of ethanol expansion. If we assume that all new corn, and only new corn, is used for ethanol production, then the GHG impacts of ethanol can be quite different from those based on the total amount of corn produced. The difference arises because additional corn is likely to be cultivated with more intensive agricultural practices. In the case of Iowa, corn expansion comes through the conversion of idle land and a rotation shift from CS to CC. In addition to higher emissions per hectare of new corn, converting CS to CC increases emissions of corn that is not destined for ethanol but must be accounted for because of expanded ethanol production. Consequently, ethanol made only from new corn results in more emissions per liter of ethanol produced as shown by the last column of Figure 3. Accounting based on new corn decreased the GHG benefits to about 22%. Given that it incorporates the impacts on corn production that is not destined for ethanol, such "new corn" accounting is, in a way, partial SWA. However, it is only partial since emission changes beyond corn production are not considered.

4.4 Results based on system-wide accounting

To perform SWA, we need information on a few other GHG emission factors besides those considered for the LCA. As we discussed in section 3, the factors are emissions from soybean production ($\hat{E}_{ag,s\_cs}$), emissions generated in the change of rotation from CS to CC ($\hat{E}_{conv,cs\_cc}$), emissions from idle land ($\hat{E}_{ag,idle}$), emissions resulting from the conversion of idle land ($\hat{E}_{conv,idle\_cc}$), emissions related to the use of soybeans ($E_{post,s}$), and emissions related to the food use of corn ($E_{post,food\_c}$).

West and Marland (2002) report the carbon emissions of corn and soybean production with respect to tillage practices in the United States. Soybean production is less energy intensive than corn and emits less carbon across all tillage practices. The difference is largely attributed to the use of N fertilizer. We combine these results with the distribution of tillage practices in Iowa as reported by the Conservation Technology Information Center (CTIC) for 2002 to calculate the tillage-weighted average emissions of corn and soybean production (Table 5). Since the West and Marland data do not include conservation tillage while the CTIC data do, we assume the emissions under conservation tillage are the same as emissions under reduced tillage. Since the latter is in general more energy intensive than the former, our assumption would overestimate emissions from corn and soybean production. From Table 5, we estimated that soybean production on average generates about 35% of the emissions generated by corn production. To obtain an estimate for the GHG emissions from soybean production, we multiply this percentage by our estimate of emissions from corn production in the CS rotation since it has been the dominant rotation. (We do not use estimates of emissions in West and Marland 2002 directly because their study has a different system boundary definition. In particular, they do not consider nitrogen emissions, but we do.)

It is not an easy task to estimate soil carbon changes on idle land at the state level because carbon differs by soil, climate, and specific vegetation on a field, which are all heterogeneous across the state. According to Brenner et al. (2001), conversion of annual cropland to grasslands, as under the Conservation Reserve Program (CRP), sequesters on average about 6.78 metric tons of CO_2e (i.e., 1.85 metric tons of carbon) per hectare per year in Iowa. In a protocol set out by the Chicago Climate Exchange, the carbon sequestration rate on CRP land is set at 2.47 tons/ha/year (CCX, 2007). In our paper, we use the latter, i.e., $\hat{E}_{ag,idle}$ = -2.47 /ton/ha/year; this means that our results on the GHG impacts of corn ethanol are on the conservative side. After 10 years, the usual contract length for the CRP program, CRP land would have added an average of 2.47 ton/ha/year of CO_2e to the soil. Upon reverting back to agricultural production, we assume that the sequestered carbon will all be released back to the atmosphere, and we assume further that this release also happens in 10 years; then, $\hat{E}_{conv,idle\_cc}$ =2.47 /ton/ha/year. Soil carbon sequestration or release is a dynamic process during which the rate of soil carbon change differs from year to year, usually at greater rates immediately following land use change. Paustian et al. (1998) suggested that when land is released from agriculture, carbon sequestration would continue for about 50 to 100 years before a new equilibrium is reached for soil carbon stock. Similarly, when land is cleared for production, the release of carbon also occurs over time (Mann, 1986). Our use of an annual average over a time period (10 years) is a simplification of this process that captures the overall change of total soil carbon stock.

The rotation effects on soil carbon stock depend on soil properties and other farm management practices like fertilizer application and tillage systems. Paustian et al. (1997) indicated that soil organic carbon was higher for continuous corn than for a corn-soybean rotation. In Hao et al. (2002), similar results were obtained for reduced tillage; the two rotations had the same soil carbon under conventional tillage. Vyn et al. (2006) reported that continuous corn did not store more soil organic carbon than rotation corn. The possible reason, they conjectured, was that continuous corn emitted more CO_2 from the soil surface than a corn-soybean rotation. Based on their analysis of a global database of long-term field experiments, including sites in the U.S. Midwest, West and Post (2002) concluded that there is no significant difference in soil organic carbon stock between CC and CS. The large amount of residue generated in a CC rotation presents a challenge for conservation tillage. Thus, the risk and magnitude of yield drag associated with CC, compared to CS, is greatest with high-residue no-till or minimum-tillage systems (Nielson et al., 2006). Thus, even though a CS rotation may result in lower soil carbon levels under the same tillage practice, overall this decrease is likely to be compensated for by more use of conservation tillage. Taking into account all these factors, we assume that $\hat{E}_{conv,cs\_cc} = 0$.

We consider SWA for two cases in Iowa. In the first case, referred to as "all CS baseline," all baseline crop production is in a CS rotation and there is no corn ethanol produced in the baseline. Hence, corn and soybean area both equal 4.605 million hectares so that their total equals the total area devoted to corn and soybeans in 2006. The scenario calls for "maximum ethanol." Corn for ethanol is created by shifting all baseline corn and soybean area to continuous corn. That is, 9.21 million hectares are shifted from CS rotation to CC. No idle land is assumed to be converted. We assume that all additional corn comes from these land use changes and no corn is diverted from food use. Furthermore, we assume that soybean consumption in Iowa does not change, which implies that any reduction in soybean production in Iowa will be made up by soybean produced somewhere else in the United States or in the world. Essentially there is no emission changes related to the food use of corn and soybeans. Calculating the weighted sum of GHG changes in a way similar to that in equation (8), we have

$$(9)\quad \Delta TE_{SWA} = \Delta TE_{LCA,c\_cc} + [9.21*0.5*(\hat{E}_{ag,s\_cs} + \hat{E}_{ag,c\_cs} - \frac{y_{cs}}{y_{cc}}*\hat{E}_{ag,c\_cc}) - (9.21)*\hat{E}_{conv,cs\_cc}]$$
$$= 10.40 + 0.06 = 10.46 \text{ (million metric tons).}$$

Table 6 lists the results for other variables in this case, including land uses, the total amount of additional corn used for ethanol, and GHG emissions. In total, the scenario generated 38.82 million metric tons more corn than the baseline. The GHG emission rate is 2.0 kg/geL, which is equivalent to a 33% reduction relative to the LCA emissions of the displaced gasoline. Thus, in this particular case, the GHG benefits of ethanol under SWA are about the same as those under LCA. Nonetheless, the apparent similarity between the results under SWA and LCA is derived through very different calculations, and the similarity could disappear if different emission coefficients were used in (9). The emissions associated with soybean production in the baseline were given as benefits from corn ethanol under SWA, while the intensification of corn production resulted in a penalty against corn ethanol's GHG impacts. Either of these quantities was large in itself (4.47 million metric tons of CO_2e), but they happened to offset each other in (9).

In the second case, we take 2006 crop production as a baseline and consider the GHG benefits of ethanol based on the additional corn generated through land use changes in 2007. We assume the total area with CS rotation was just double that of soybean area; then the area for CS rotation was 8.22 million hectares in 2006 and 7.12 million hectares in 2007 (see Table 2). This implies that 1.1 million hectares was shifted from CS to CC. The difference in total area between the two years (0.14 million hectares) was assumed to have been converted from idle land to continuous corn. As in the previous case, food use of corn and soybeans is assumed to be the same as in the baseline. Then, we can compute corn ethanol's GHG benefits for this case as

$$\begin{aligned} \Delta TE_{SWA} = \Delta TE_{LCA,c\_cc} & + [1.1 * 0.5 * (\hat{E}_{ag,s\_cs} + \hat{E}_{ag,c\_cs} - \frac{y_{cs}}{y_{cc}} * \hat{E}_{ag,c\_cc}) \\ & - (1.1) * \hat{E}_{conv,cs\_cc} + 0.14 * (\hat{E}_{ag,idle} - \hat{E}_{conv,idle\_cc})] \\ = 1.76 - 0.70 = 1.06 & \text{ (million metric tons).} \end{aligned} \tag{10}$$

Land use changes and GHG results are presented in Table 6. Dividing total GHG emissions by the ethanol produced from the additional corn, we obtain the GHG benefits for this case: 0.58 kg CO_2e per liter of gasoline displaced. This amounts to a 20% reduction from the LCA emissions of gasoline. This reduction is smaller than in the previous case because the increase in emissions related to conversion of idle land is relatively more important given the much smaller total emission reduction in this case.

4.5. The impacts of geographical boundaries

One potential criticism of the analysis presented in the previous section could be that the geographic boundaries put on the problem are too restrictive. After all, in both cases analyzed, most of the additional corn for ethanol production is made available by reducing soybean acreage. Furthermore, soybean consumption is held to be the same as in the baseline scenarios for both cases. But if soybean consumption does not change in Iowa, then additional land will have to be devoted to soybean production in other regions of the United States or in South America.

Expansion of the SWA boundaries to include these indirect effects of expanded soybean production area is beyond the scope of this study. However, we can make some rough calculations. Suppose that the geographical boundary is expanded so that emissions from soybean expansion outside Iowa will have to be considered. Then the credits given to ethanol's GHG benefits in SWA for soybean production would have to be taken away. If soybean acreage expanded outside of Iowa emits GHGs at the same rate as that used in our previous analysis, then broadening the geographical boundary this way will reduce the GHG benefits of Iowa corn ethanol to 19% for the all-CS baseline case and 9% for the 2006 baseline case.

If we further assume that land used for soybean expansion has never been tilled, and that the release of carbon in the untilled land is equal to the release of carbon from CRP land when it is tilled, then ethanol's benefits have to be reduced even more. Suppose expanded soybean acreage has the same yield as that in Iowa, which implies that new soybean production area outside Iowa has to equal the amount of reduction in soybean area in Iowa to maintain total soybean production. Then emissions from corn ethanol are higher than those of gasoline by 17% and 16% for the all-CS baseline case and the 2006 baseline case, respectively. Of course, emissions associated with soybean production and conversion of grassland to soybean production will depend on the soil and climate condition of the relevant regions. But our estimates show how such benefits can be calculated and the possible magnitude of these numbers.

5. Conclusions

The degree to which corn ethanol reduces greenhouse gas emissions depends on how corn is produced, how corn is processed into ethanol, and what emissions would be without corn ethanol. Life cycle analysis takes into account the first two factors, but not the third. But the third factor may be the most important determinant. The degree to which LCA-estimated emissions differ from those estimated with system-wide accounting can vary widely depending on the situation analyzed.

LCA estimates of the reduction in GHG emissions of corn ethanol themselves can vary widely. The GHG reduction of corn ethanol produced from Iowa corn vary according to the year analyzed, whether corn is grown in rotation with soybeans, and whether the average or marginal agronomy emissions of corn are measured. Corn grown after a crop of soybeans in Iowa emits 35% less CO_2e in the agronomy stage than corn grown after a crop of corn. Hence, Iowa corn grown in 2007 had higher average emissions than Iowa corn grown in 2006 because Iowa moved to more continuous corn spurred by the increased demand for ethanol. LCA of the marginal corn that Iowa farmers grew in 2007 to meet ethanol demand (rather than the 2007 average corn) reduces the net GHG reduction of corn ethanol relative to gasoline from 40% to 22%.

Moving to SWA accounting involves comparing total baseline emissions and emissions with corn ethanol. Thus, care must be taken in specifying both the baseline and the scenario. If baseline ethanol production is zero, and all baseline Iowa corn is grown in a corn-soybean rotation, then a shift to continuous corn to provide corn for ethanol production would reduce net GHG emissions relative to baseline results by approximately 33% per liter of gasoline displaced. If 2006 planted acreage and ethanol production is taken to be the baseline and the 2007 changes in Iowa acreage represent the scenario to be analyzed, then emissions are reduced by 20% per liter of gasoline displaced. The difference results from the fact that 140,000 hectares of idle land were brought into production in 2007.

For both SWA and LCA, the definition of boundaries is a key factor in determining estimated emissions. Which processes to include in the life cycle of ethanol can make a big difference in LCA results. There is a general consensus on the definition of system boundaries for LCA (e.g., Farrell et al., 2006). As we have demonstrated, SWA results are affected by the use of baseline and the definition of geographical boundaries. Whether there are positive GHG benefits and the size of such benefits from Iowa corn ethanol depend on the geographical region defined for analysis. This indicates that clearly identifying system boundaries is as important for SWA as for LCA.

Table 1. Definitions of terms regarding emissions coefficients

Terms	Definition
$E_{LCA,eth\_rotation}$	LCA emissions of ethanol (kg/geL) from corn grown with a specific rotation (rotation=CC or CS)
$E_{ag,c\_rotation}$	Emissions of ethanol (kg/geL) in agronomy phase (from corn grown with a specific rotation, CC or CS)
$E_{post,eth}$	Emissions of ethanol (kg/geL) in post-agriculture phase
$\hat{E}_{ag,s\_cs}$	Emissions of soybeans (kg/geL) in agronomy phase in CS rotation
$\hat{E}_{ag,c\_cs}$	Emissions of corn (kg/ha) in agronomy phase in CS rotation
$\hat{E}_{ag,c\_cc}$	Emissions of corn (kg/ha) in agronomy phase in CC rotation
$\hat{E}_{ag,idle}$	Emissions of idled land (kg/ha)
$\hat{E}_{conv,idle\_cc}$	Emissions of land (kg/ha) in the conversion from idle to CC rotation
$\hat{E}_{conv,cs\_cc}$	Emissions of land (kg/ha) in the conversion from soybean to corn
$E_{post,food\_c}$	Emissions of corn (kg/ton) used for food in post-agriculture phase
$E_{post,s}$	Emissions of soybeans (kg/ton) used for food in post-agriculture phase
$E_{LCA,gas}$	LCA emissions of petroleum gasoline (kg/geL)

Table 2. Corn and soybean areas in Iowa (million hectares)

Year	Corn	Soybean	Total
2006	5.10	4.11	9.21
2007	5.79	3.56	9.35

Table 3. Iowa's trend corn yields for 2007, inferred distribution and input use

	Corn-Soybean Rotation			Corn-Corn Rotation		
Yield Classes	Lower Yields	Middle Yields	Upper Yields	Lower Yields	Middle Yields	Upper Yields
Yields (ton/ha)	9.68	10.54	11.17	8.71	9.49	10.05
N fixed (kg/ha)	146	146	146	202	202	202
N varied (kg/ha)	129	146	163	185	202	219
P (kg/ha)	62	67	78	49	62	67
K (kg/ha)	45	56	62	45	50	56
Limestone (kg/ha)	647	647	647	647	647	647

Table 4. Greenhouse gas emissions in the agronomy phase (kg CO_2e/ton of corn)

	Land Class (Type of Yields)	Emissions (uniform N rate)	Emissions (varied N rates)
$\hat{E}_{ag,c\_cs}$	High	247.64	264.17
	Middle	260.24	260.24
	Low	281.5	262.6
	Average	262.99	262.2
$\hat{E}_{ag,c\_cc}$	High	334.25	352.76
	Middle	352.76	352.76
	Low	381.5	360.24
	Average	356.3	355.12

Table 5. Tillage practices in Iowa and emissions from corn and soybeans

Tillage Practice	Soybean emission (kg/ha/yr)	Corn emission (kg/ha/yr)	Tillage of soybeans in Iowa	Tillage of corn in Iowa
Conventional	106.99	228.07	7.6%	22.4%
Reduced	86.98	246.11	20.7%	35.6%
Conservation	86.98	246.11	43.2%	24.3%
No till	70.92	225.11	28.3%	17.7%

Source: The source of the soybean and corn emissions is West and Marland 2002.

Table 6. System-wide accounting results based on two different baselines and scenarios

Change from Baseline	Maximum Ethanol Relative to No Ethanol Baseline	2007 Situation Relative to 2006 Baseline
CC area (million hectare)	9.21	1.23
CS area (million hectare)	-9.21	-1.09
Idle land area (million hectare)	0	-0.14
Corn production (million metric tons)	38.82	6.55
Total GHG emissions (million metric tons CO2e)	10.46	1.06
GHG emissions (kg CO_2e per liter[a] of ethanol)	1.99	2.38
GHG reduction per liter of gasoline displaced	32.6%	19.6%

[a]As in rest of the paper, here liter means "gasoline-equivalent liter"—the amount of ethanol that is equivalent to 1 liter of gasoline in energy content.

Figure 1. Illustration of system-wide accounting—baseline

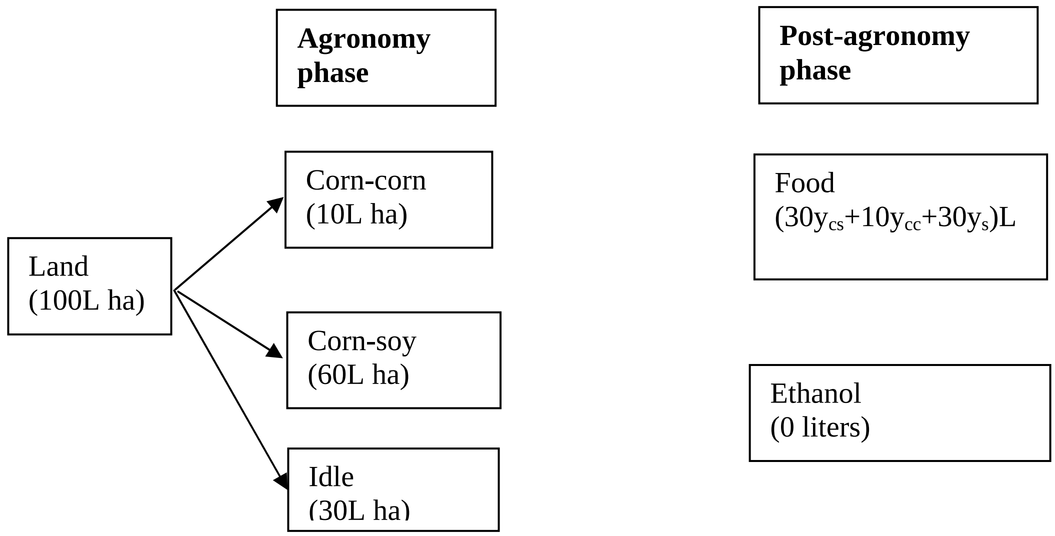


Figure 2. Illustration of system-wide accounting—change from baseline

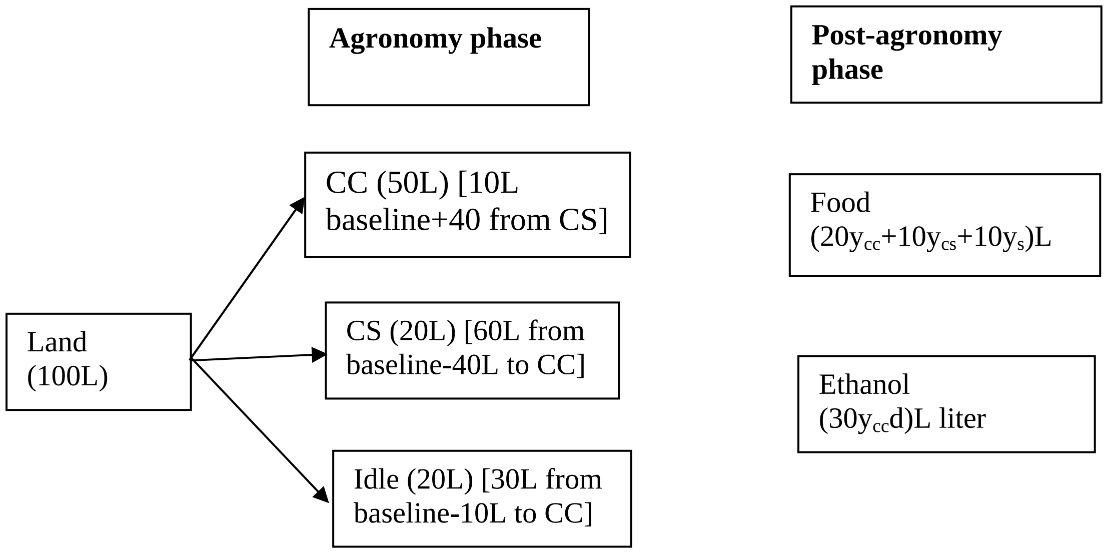
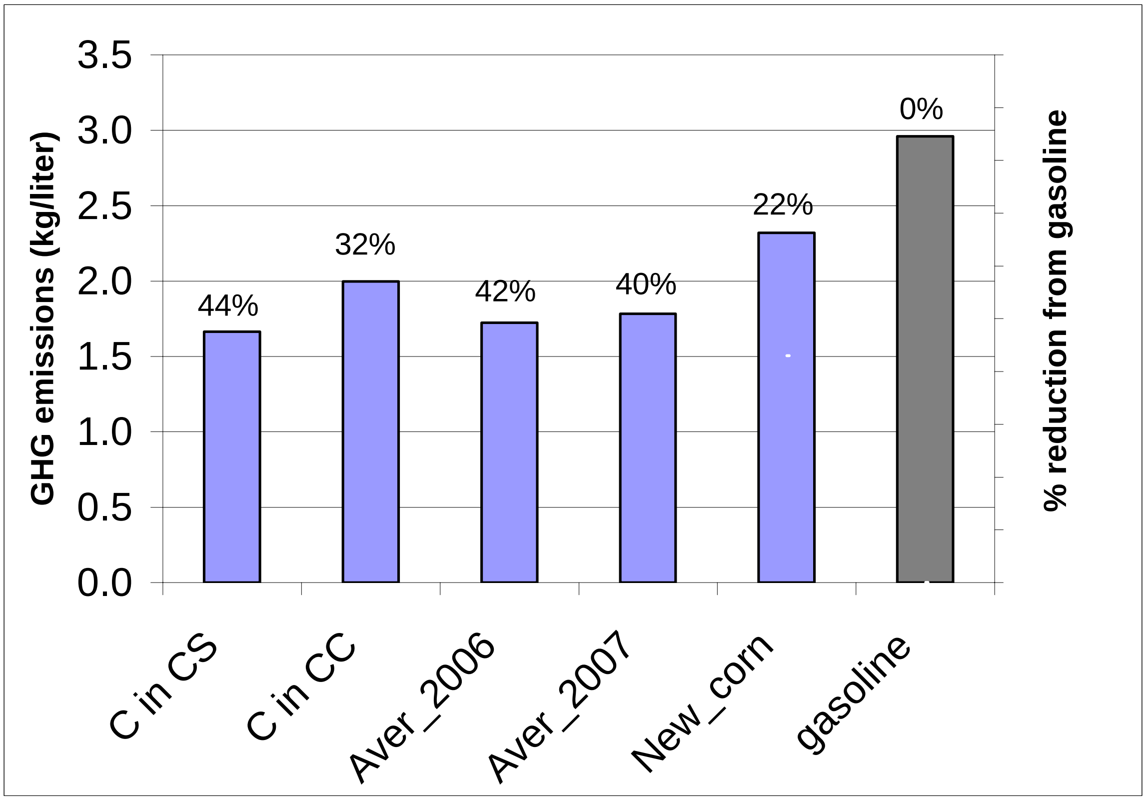


Figure 3. The greenhouse gas emissions of corn ethanol and percentage reductions from gasoline emissions



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